NAVY EXPERIMENTAL DIVING UNIT
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MANNED EVALUATION OF THE CARLETON 1.3 ATA PO_2 PRIMARY ELECTRONICS ASSEMBLY WITH THE MK 16 UNDERWATER BREATHING APPARATUS

E. T. LONG
M. J. FENNEWALD

MARCH 2000

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The Navy Experimental Diving Unit (NEDU) evaluated a prototype Primary Electronics Assembly (PEA) for the MK 16 Underwater Breathing Apparatus (UBA) which can reduce the in-water decompression obligation by increasing the operating partial pressure of oxygen (PO_2) level from 0.75 atmospheres absolute (ATA) to 1.3 ATA. Upon descent to a depth of 33 ± 2.4 feet sea water (fsw) (10 ± 0.73 meters of seawater (msw)) the electronics switch from 0.75 to 1.3 ATA PO_2 set point control that is maintained until the diver ascends above 12 (± 2) fsw (4 ± 0.60 msw), where the electronics switch back to the 0.75 ATA PO_2 set point mode.

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Manned testing of the MK 16 PEA was conducted in the NEDU Ocean Simulation Facility (OSF) with water temperature maintained at 70 - 75°F (21.1 - 23.9°C). Test dives at 50 and 100 fsw (15 and 30 msw) were on a nitrogen and oxygen (N_2O_2) mix using air as diluent, and at 200 and 300 fsw (61 and 91 msw) using a 88% helium and 12% oxygen (88/12 HeO_2) mix as diluent. MK 16 electronic signal lines from the UBA sensors were tapped through an in-house designed isolation unit for data collection. Oxygen consumption rates of 0.75 to 3.28 liters per minute (L/min) were achieved with an underwater cycle ergometer.

The PEA reliably switched between control set points as designed. Upon descent, the PO_2 never exceeded the maximum overshoot performance goal of 1.9 ATA, except at 300 fsw in HeO_2 where the PO_2 reached a maximum of 1.98 ATA. Upon ascent, PO_2 did not fall below 0.2 ATA, thereby meeting this performance goal. The time weighted average PO_2 after UBA stabilization at depth was consistently maintained at 1.30 ± 0.05 ATA, while PO_2 was consistently maintained within the control band limit of 1.15 - 1.45 ATA. In summary, the MK 16 MOD 0 PEA controls the PO_2 according to the established PO_2 control band goals and NEDU recommends adopting the MK 16 MOD 0 1.3 ATA Primary Electronics Assembly for Fleet use.

CONTENTS

	Page No.
INTRODUCTION	1
METHODS	2
RESULTS	7
DISCUSSION	24
CONCLUSIONS	26
RECOMMENDATIONS	26
REFERENCES	27

FIGURES

FIGURE		Page No.
1	Errant fuel cell spikes.	8
2	Diver Profile During Descent Breathing Chamber Air during 50 fsw ENG609RB	12
3	Diver Profile During Descent Breathing Chamber Air during 50 fsw ENG610RB	13

TABLES

TABLE		Page No.
1	PO_2 Average during First 10 Control Cycles at 50 fsw (Maximum Depth).	10
2	PO_2 Average overall Control Cycles at 50 fsw (Maximum Depth).	11
3	Minimum and Maximum PO_2 Values Recorded during Entire Dive at 50 fsw.	14
4	PO_2 Average during First 10 Control Cycles at 100 fsw (Maximum Depth).	15
5	PO_2 Average over all Control Cycles at 100 fsw (Maximum Depth).	16
6	PO_2 Average over all Control Cycles at 100 fsw (Maximum Depth).	16
7	PO_2 Average during First 10 Control Cycles at 200 fsw (Maximum Depth).	18

INTRODUCTION

The Navy Experimental Diving Unit (NEDU) has been directed to test and evaluate a prototype Primary Electronics Assembly (PEA), manufactured by Carleton Industries Inc., for use in the MK 16 Underwater Breathing Apparatus (UBA)[1,2]. The primary goal of the MK 16 UBA Product Upgrade is to reduce the in-water decompression obligation encountered when diving to depths deeper than 200 feet of sea water (fsw). This can be accomplished by increasing the operating partial pressure of oxygen (PO_2) level from 0.75 Atmospheres Absolute (ATA) to 1.3 ATA, reducing decompression obligation by as much as 40%, resulting in increased diver safety and capability.

The Carleton PEA upgrade operates in two different set point modes. One is the 0.75 ATA PO_2 mode for surface and shallow water, and the other is the 1.3 ATA PO_2 mode for deeper water. This upgrade incorporates a depth sensor that automatically switches the UBA between these two modes. At initial start up, the electronics are in the 0.75 ATA PO_2 set point mode. On descent, the electronics are designed to switch to 1.3 ATA PO_2 set point control at a depth of 33 ± 2.4 fsw (10 ± 0.73 meters of seawater (msw)). This set point is maintained until the diver ascends above 12 ± 2 fsw (4 ± 0.60 msw), where the electronics switch back to the 0.75 ATA PO_2 set point mode.

Based on unmanned testing, we determined[3] that the PEA is capable of reliably switching from 0.75 ATA PO_2 to 1.3 ATA PO_2 at 33 fsw during descent, and switch back to a 0.75 ATA PO_2 at 12 fsw upon ascent. The PEA also reliably maintained a stable PO_2 in the UBA breathing loop during unmanned testing that was within the control parameters. (See **PURPOSE** Section for control parameters).

UBA DESCRIPTION

The MK 16 Underwater Breathing Apparatus (UBA) is a low magnetic signature (LO-MU), closed circuit, mixed gas, and constant partial pressure of oxygen underwater life support system. The UBA was built to support the low magnetic and acoustic signature requirements of U.S. Navy Explosive Ordnance Disposal (EOD). The breathing medium is kept at a predetermined partial pressure of oxygen (PO_2) using oxygen sensors that monitor, evaluate, and control the level via a battery operated electronic module.

PURPOSE

The purpose of this study was to verify that the PEA was able to maintain a 1.3 ATA PO_2 set point in the UBA breathing loop during manned diving operations. Maintenance of 1.3 ATA PO_2 should remain within the following control parameters[4]:

a. After UBA stabilization at depth, time-weighted average PO_2 remains between 1.25 and 1.35 ATA (1.30 ± 0.05 ATA).

b. After UBA stabilization, the PO_2 range does not fall below 1.15 ATA or exceed 1.45 ATA at any time.

c. The PO_2 does not exceed 1.9 ATA during descent at 60 feet per minute (fpm).

d. The PO_2 does not to fall below 0.2 ATA during ascent at 30 fpm.

METHODS

GENERAL

Manned testing of the MK 16 PEA was conducted at 50 and 100 fsw (15 and 30 msw) on nitrogen and oxygen (N_2O_2) mix using air as diluent. For 100 fsw dives requiring Decompression, USN Standard Air Decompression Tables were used. Testing at 200 and 300 fsw (61 and 91 msw) was completed on helium and oxygen (HeO_2) with an 88% helium / 12% oxygen (88/12 HeO_2) as diluent. All dives were conducted in the NEDU Ocean Simulation Facility (OSF). The wet chamber water temperature was set between 70 -75°F (21.1 - 23.9°C). Diver dress varied from a minimum of "dive skins," to a full wet suit with booties and gloves. The decompression tables that were used had been man tested, although they have not undergone a full validation series[5].

All divers were qualified U.S. Navy divers who had undergone familiarization training on the MK 16 with the new PEA. A minimum of 24 hours was required between each experimental dive. The exception to this 24-hour rule was for dives conducted on N_2O_2 (50 and 100 fsw); these dives followed U.S. Navy Standard Air Decompression Tables which allows a minimum of 12 hours between dives[6,7]. The MK 24 Full Face Mask (FFM) was configured for communications between the divers and Control, with secondary communications via the in-water hydrophone and standard U.S. Navy hand signals. The divers were usually monitored with underwater cameras.

Most divers completed a maximum oxygen consumption ($\dot{V}O_2$ max) test based on a progressive intensity, continuous effort treadmill protocol[8] prior to starting this study. This $\dot{V}O_2$ max testing was used to determine the diver's maximum heart rate (HR_{max}). For those divers who did not complete a $\dot{V}O_2$ max test, the individual's predicted heart rate was calculated using the formula (220-age). During the 50 and 100 fsw exercise protocols, divers worked for 20 minutes each at 40 and 60% of their $\dot{V}O_2$ max heart rates. During the 200 and 300 fsw dives, work rates were based on 60% of $\dot{V}O_2$ max heart rate.

INSTRUMENTATION

A data collection system was connected to the MK 16 and electronic signal lines were tapped through an in-house designed isolation unit. The unit uses standard

MK 16 input and output connectors, allowing simple series connection into the primary and secondary whips. The unit was powered from the MK 16 primary battery and had a waterproof output umbilical for routing signals to the surface. Low power, high input impedance instrumentation amplifiers were used as buffers to avoid loading of the signals and to ensure minimum drain to the rigs battery. The MK16 primary and secondary display parameters were monitored real-time and displayed on the medical deck data acquisition systems (DAS) computers. The data was logged to hard drive for post dive analysis.

The MK 16 was instrumented with a 0-5000 psig Druck pressure gauge (Druck, Inc., New Fairfield, CT) was used to monitor oxygen bottle pressure in the MK 16 for calculating oxygen consumption. Another 0-5000 psig Druck pressure gauge was used to monitor diluent bottle pressure in the MK 16. A YSI thermistor was used to monitor the wet pot temperature in the area of the MK 16 divers.

In addition a Teledyne R-10 coarse temperature compensation and thermistor was placed in the inhalation side of the breathing loop to provide an independent measure of PO_2 (P_iO_2) within the UBA. The independent oxygen sensor was calibrated by flowing a range of calibration gases from 0 to 95% O_2 over this sensor. The information from the independent fuel cell was obtained to ensure that a PO_2 of at least 1.3 ATA was being breathed by the diver for the purpose of the decompression table validation study.

Two different DAS computers were utilized during this series. One specifically monitored and logged engineering data from the MK 16 PEA that included depth, wet pot temperature, MK 16 battery, diluent and O_2 bottle pressure, dive time, O_2 addition valve status (open/closed), and status of PO_2 control point (0.75 or 1.3 ATA), and MK 16 fuel cell readings. The other DAS monitored and logged the physiological and environmental data depth of wet pot temperature, dive time, as well as UBA O_2 bottle pressure used for calculating O_2 consumption and the independent fuel cell readings.

Standard pre-dive procedures[9] were modified to incorporate the use of a calibration cup over the sensor tower and flowing 95% oxygen in nitrogen calibration gas over the sensors at five L/min Standard Temperature Pressure Dry (STPD). A water manometer connected to the calibration cup insured that the sensors were not overpressurized. Gas was allowed to flow for a period of five minutes before the thumb wheel switches were adjusted on the PEA. This was deemed the best method[10] of achieving a stable reference PO_2 for adjusting the sensor gain switches of the secondary display, leading to a more accurate primary electronics calibration. This calibration procedure was incorporated throughout the series of unmanned and manned test dives.

All divers were fitted with ECG leads. Heart rate monitoring was performed with the Quinton (Quinton Instrument Co., Bothell, WA) ECG telemetry system. Although we intended to use steady-state heart rate, and adjust the workload to achieve the desired percentage of oxygen consumption, during this study heart rate appeared to be

insensitive to work rate. Therefore, actual computed steady-state oxygen consumption was used to adjust the watt load.

Three electrically braked pedal ergometers (W. E. Collins, Brumtree, MA) were positioned within the wet pot, placed on a high stand in a 0° (horizontal) incline. The applied watt load was recorded manually in a dedicated logbook along with divers' heart rates associated with that wattage.

The platform was staged so the MK 16 UBA was completely submerged when the diver was in position on the ergometer. The actual water depth was measured prior to diving, used as the offset for diver depth in the medical deck DAS, and recorded in the log file for each corresponding diver. Testing was accomplished in order of increasing depth to allow "work-ups" to 300 fsw.

A 0-150 psia Druck absolute pressure transducer located in C chamber provided input to data acquisition computers for calculating chamber depth.

The physiological DAS computer calculated oxygen consumption using the following formula, the oxygen bottle pressure and water temperature obtained from sensors described above:

$$\dot{V}O_2 = [(P_{start} - P_{finish}) / t] \times [\dot{V}_b/14.7 \text{ psig}] \times [273/ (T+273)]$$

Where:

$\dot{V}O_2$ - oxygen consumption rate (lpm)
P - oxygen bottle pressure (psig)
t - time (minutes)
$\dot{V}_b$ - oxygen bottle's floodable volume (liters)
T - temperature in °C

We tapped all UBAs with a sample line routed to a mass spectrophotometer as a safety precaution. We never sampled gas unless we believed the UBA was not maintaining correct PO_2, or carbon dioxide levels were rising.

Average PO_2 values for each fuel cell were calculated for two different periods during the dive. The first average was based on the first "10 control cycles" once the UBA stabilized at depth. The first 10 control cycles were defined as commencing when the O_2 add valve opens for the first time at stabilized depth (maximum depth), and covers the next ten open and close cycles of the oxygen addition valve. PO_2 averages for each fuel cell were also calculated for the entire "bottom control period". This bottom control period commences with the start of the first 10 control cycles, and ends when the diver begins ascent.

It was anticipated that diver thermal comfort would not be a problem during descent and Bottom Time (BT) because the diver would be exercising (i.e., pedaling the pedal ergometer). However, hot water hoses were available to prevent divers from becoming unreasonably cold during ascent and in-water decompression.

PROCEDURES

Descent/Ascent Rates

All dives were conducted utilizing the fastest descent rate we could attain in the OSF, not to exceed 60 fsw per minute (fpm). We maintained an ascent rate as close to 30 fpm as possible for ascent from the bottom and between decompression stops.

Calibration Procedures

The MK 16 oxygen sensors were calibrated on the medical deck prior to the dive. Though the rig was setup in the dive locker, the medical deck DAS needed to be calibrated using the output of the MK 16 oxygen sensors. The MK 16 UBA oxygen sensors were calibrated with a cup using 95% oxygen. Calibration procedures for the independent oxygen sensor also used a calibration cup, but we exposed this sensor to a span of calibration gases ranging from 0% to 100% oxygen prior to installation into the MK 16. All calibration parameters were recorded on the pre-dive check sheet for that UBA. All other instrument calibration procedures was performed per the Medical Department Instrumentation Standard Operating Procedures[11].

Dive Procedures

Medical Deck instrumentation was calibrated prior to starting the first dive of the day. After the MK 16 and MK 24 FFM were pre-dived[9], all UBA instrumentation was checked, and all signal paths from each UBA were verified.

One trunk tender and one stand-by diver were used for all dives. When the divers were properly dressed, they entered the OSF complex, all the equipment was checked, the diver went "on-gas," entered the water, and the medical deck DAS logs were started. Once in-water checks were complete, the dive watch supervisor (DWS) directed the diver to leave the surface, mount the appropriate ergometer, and indicate when ready to travel. The dive time started when the complex left the surface.

We expected descent might be stopped for various reasons, including divers unable to equalize middle ear pressure. During the 50 and 100 fsw dives we imposed no specific time period required to reach the bottom, though 60 fpm was the desired rate and goal. However, during the deeper dives where bottom time was at a premium, if divers were not at maximum depth within 10 minutes of leaving surface, that particular dive was terminated, and the divers were returned to the surface after completing any required decompression. A complete copy of the 1.3 ATA PO_2 decompression tables[5] was provided to the control room in case we aborted a dive.

Divers executed two different rest/work protocols, depending on the depth and diluent gas, as follows:

Protocol 1 (50 and 100 fsw N_2O_2):

Time		Activity
As required		Descent to 50 or 100 fsw
1-2 min		preparing to start work
40 min	Goal	Cycle at 40% - 60% $\dot{V}O_2$ max (at various workloads)
Variable		Rest
As required		Ascent

Protocol 2 (200 and 300 fsw HeO_2):

Time	Activity
As required	Descent (not to exceed 10 min)
1-2 min	preparing to start work
20 min	Cycle at 60% $\dot{V}O_2$ max (based on previous dives but variable workloads)
Variable	Rest
As required	Ascent

While working, the diver pedaled continuously at 60 ± 5 rpm and at various wattages depending upon their computed oxygen consumption rate.

Total bottom time was at a premium for the 200 and 300 fsw dives due to the required decompression. Therefore, bottom time for these dives was restricted to 40 minutes at 200 fsw and 30 minutes at 300 fsw.

At the completion of the work/rest cycle, divers subsequently remained at rest during ascent and any decompression stops. When the divers indicated they were ready to leave the bottom, the complex started traveling at 30 fpm to the first decompression stop. This ascent rate was used throughout the remainder of the dive.

Upon completion of the dive day, all data were archived and a copy of the files made available to the Principal Investigator (PI) for further data reduction and analysis.

RESULTS

GENERAL

During this study, the DAS computers occasionally recorded data that reflected voltage spikes or some other electronic aberration inherent in the data collection system. These spikes did not represent the MK 16 secondary fuel cell readings. Therefore, all errant spike fuel cells were dropped from the analysis and not used to calculate average or maximum PO_2 during any phase of the dive. Figure 1 shows affected fuel cell readings rapidly rising and then falling far beyond the response capacity of the fuel cells.

50 fsw

Thirty-two dives were conducted at 50 fsw in the OSF. For the purpose of this report, a "dive" refers to a single diver. Thus, during each OSF compression we collected two data points or "dives." However, ascent and descent rates were calculated based on the number of OSF compressions, and not the number of "dives" because both divers had the same ascent and descent rates. Of the dives conducted at 50 fsw, two were aborted one for diver discomfort in the UBA, and the other because the diver suspected a "caustic cocktail." On both occasions, no UBA malfunctions were discovered post-dive. The DAS computers also failed to record two other dives, so those dive data were lost. This left 28 data acquisition dives; their results are presented below. The average bottom time (BT) for this series of dives was approximately 52 minutes.

Across 15 dives, we achieved a 33.0 fpm average rate of descent, with a range of 6.9 to 53.8 fpm. The average depth of switching from 0.75 to 1.3 PO_2 control set point was 30.6 fsw, with a range of 28.7 – 31.7 fsw. The average rate of ascent was 23.9 fpm, with a range of 18.1 to 27.3 fpm. The average depth of switching back from 1.3 to 0.75 PO_2 control set point on ascent was 16.7 fsw, with a range of 15.1 to 17.8 fsw.

During the 50 fsw dives, the divers pedaled at workloads ranging from 10 to 115 watts. Oxygen consumption averaged 1.67 liters/minute (L/min) ranging from 0.75 to 2.87 L/min. No effort was made during this series to group dives by $\dot{V}O_2$ because UBA control band goals[4] assume metabolic O_2 consumption falls between 0.5 and 3.0 L/min.

The average overshoots for PEA 419, PEA 0700, PEA 957, and PEA CTI-1 were to 1.38 ATA, 1.36 ATA, 1.39 ATA, and 1.38 ATA respectively. The maximum overshoot for any single fuel cell was 1.68 ATA. In all instances where the overshoot exceeded 1.40 ATA, the time required for the diver to breathe the UBA down below 1.40 ATA was less than three minutes.

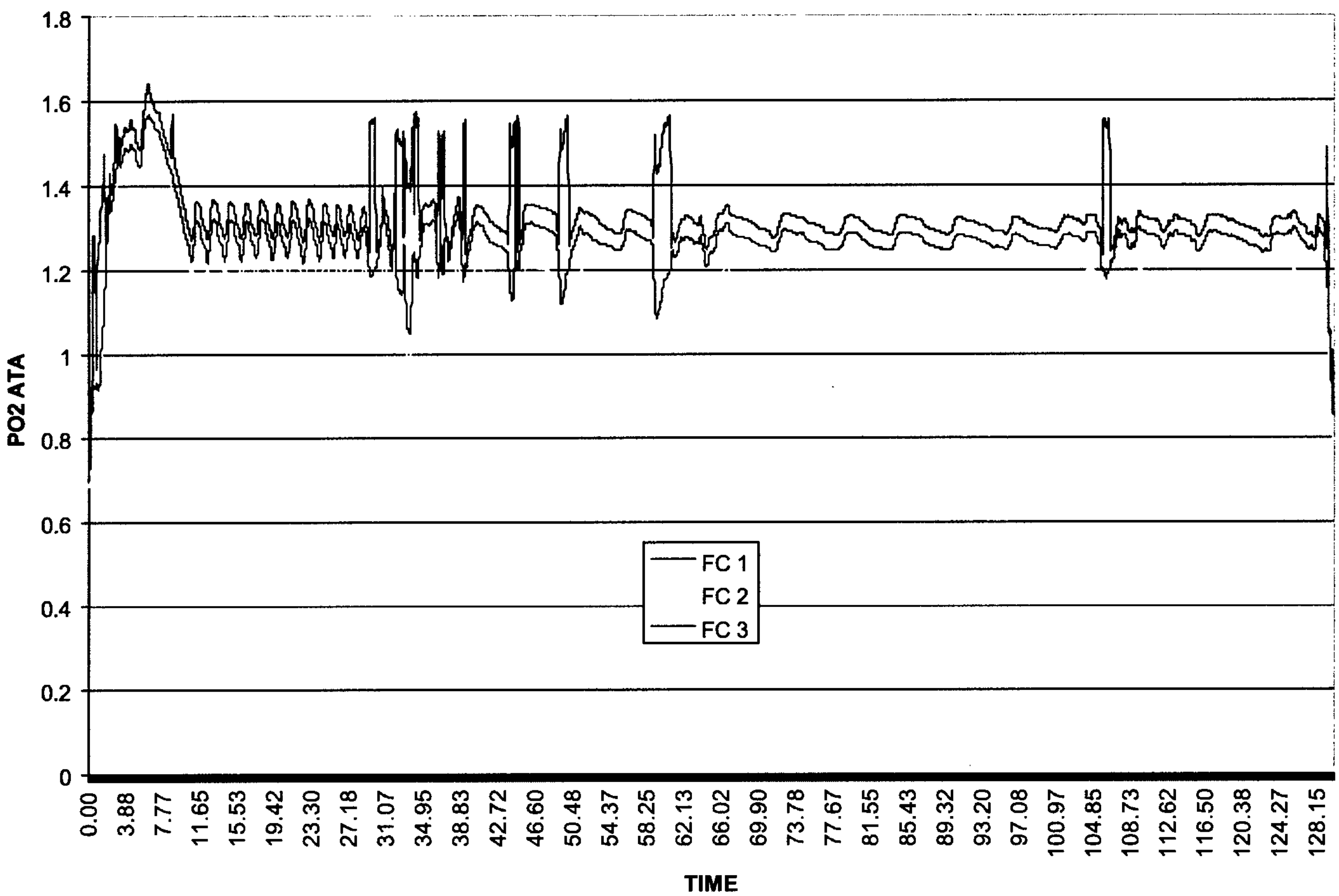

Figure 1. Errant Fuel Cell Spikes during 200 fsw dive with PEA 419 (file ENG622RB)

Although the descent rate was less than the goal rate of 60 fpm (average 33.0 fpm over 16 dives), PO_2 overshoot (1.38 ATA PO_2) remained well below the maximum 1.9 ATA PO_2 specified by PEO-EOD[4]. The single fastest descent recorded was 53.8 fpm. During this dive the highest PO_2 reading on an individual fuel cell was 1.44 ATA which occurred with fuel cell No. 3 PEA 957. However, the largest PO_2 overshoot, 1.68 ATA occurred during a dive with a descent rate of 6.9 fpm, the slowest descent rate recorded for the 50 fsw series.

The PEAs also reliably demonstrated the ability to switch back from 1.30 to 0.75 ATA PO_2 control set point on ascent, even though the ascent goal of 30 fpm was not achieved. The single fastest ascent rate recorded was 27.3 fpm with PEAs 0700 and CTI-1, where undershoot only reached 0.57 ATA and 0.54 ATA respectively.

Although the ascent rate goal of 30 fpm was not obtained during this study, it would seem reasonable that during an ascent rate of 30 fpm the UBA would be able to maintain above 0.2 ATA PO_2. Additionally, current EOD operational tactics required the diver to manually add O_2 prior to leaving the bottom. The EOD diver continues to add O_2 until he has a flashing green light on his primary display. It would be expected that this tactic would continue to be used with the 1.3 PEAs to ensure the diver does not become hypoxic during ascent.

The performance specification of the MK 16 MOD 0 requires a stabilized UBA PO_2 pattern of 1.3 ± 0.05 ATA. After UBA stabilization, the time weighted average PO_2 remained within 1.30 ± 0.05 ATA on all the 50 fsw dives, with one exception. Initially fuel cell No. 2 in PEA 0700 time weighted average PO_2 was outside the control band limit of 1.35 ATA by 0.01 ATA PO_2. However, over the course of the entire control bottom time, this particular fuel cell fell within the control band.

Table 1 shows average PO_2 values for all three UBA fuel cells for that particular PEA during the first 10 control cycles. Minimum and maximum values are those occurring during these 10 control cycles, and represent the limits of the UBA control.

TABLE 1. Average PO_2 during First 10 Control Cycles at 50 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
419	AVG 10 (SD)	[12] 1.29 (0.04)	[12] 1.28 (0.04)	[12] 1.31 (0.04)
	MIN 10	1.21	1.20	1.22
	MAX 10	1.41	1.42	1.43
957	AVG 10 (SD)	[8] 1.26 (0.07)	[11] 1.27 (0.05)	[11] 1.28 (0.04)
	MIN 10	1.15	0.97	0.98
	MAX 10	1.45	1.41	1.42
CTI-1	AVG 10 (SD)	[2] 1.35 (0.01)	[2] 1.24 (0.06)	[2] 1.33 (0.04)
	MIN 10	1.31	1.17	1.27
	MAX 10	1.38	1.33	1.39
0700	AVG 10 (SD)	[3] 1.26 (0.07)	[3] 1.36 (0.03)	[3] 1.32 (0.02)
	MIN 10	1.15	1.29	1.26
	MAX 10	1.37	1.48	1.39

AVG 10 = Average PO_2 over First 10 control cycles;
MIN 10 = minimum PO_2 recorded during first 10 control cycles;
MAX 10 = maximum PO_2 recorded during first 10 control cycles;
numbers in [ ] indicate the number of dives averaged;
numbers in ( ) indicate one standard deviation.

Table 2 shows average PO_2 values for all three UBA fuel cells for the entire "bottom control time." Again, bottom control time is defined as the period of time from when the UBA starts controlling, i.e., the start of the 10 control cycles, until the diver leaves the bottom. The minimum and maximum values shown were measured during this bottom control time.

TABLE 2. PO_2 Average overall Control Cycles at 50 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
419	AVG ALL (SD)	[12] 1.29 (0.04)	[12] 1.28 (0.05)	[12] 1.32 (0.05)
	MIN ALL	1.21	1.00	1.06
	MAX ALL	1.41	1.46	1.54
957	AVG ALL (SD)	[8] 1.26 (0.07)	[11] 1.27 (0.05)	[11] 1.29 (0.04)
	MIN ALL	1.15	0.97	0.98
	MAX ALL	1.45	1.43	1.44
CTI-1	AVG ALL (SD)	[2] 1.35 (0.01)	[2] 1.20 (0.03)	[2] 1.33 (0.04)
	MIN ALL	1.31	1.12	1.27
	MAX ALL	1.38	1.33	1.39
0700	AVG ALL (SD)	[3] 1.26 (0.07)	[3] 1.35 (0.03)	[3] 1.32 (0.02)
	MIN ALL	1.15	1.21	1.19
	MAX ALL	1.37	1.48	1.39

AVG ALL = Average PO_2 over entire time at 50 fsw after UBA stabilization;
MIN 10 = minimum PO_2 recorded during entire time at 50 fsw after UBA stabilization;
MAX 10 = maximum PO_2 recorded during entire time at 50 fsw after UBA stabilization;
numbers in [ ] indicate the number of dives averaged;
numbers in ( ) indicate one standard deviation.

After UBA stabilization, the PO_2 range did not fall below 1.15 ATA with the exception of fuel cells No. 2 and No. 3 on PEA 957. During this series of dives, there were two divers who had minimums below 1.15 ATA. However, both of these divers experienced difficulty in equalizing their ears during descent. Therefore, the divers came off the UBA and breathed chamber air during the remainder of their respective descents. Consequently, when the divers went back to breathing UBA, the PO_2 was lower than normal with a diver breathing the UBA during descent. The O_2 add valve opened immediately when the divers went back on the UBA, but by definition, this O_2 add valve opening constituted the start of the 10 control cycles. If these dives are viewed after the UBA stabilized, then the UBA maintained PO_2 above the lower control limit. These dives are shown graphically in Figures 2 and 3.

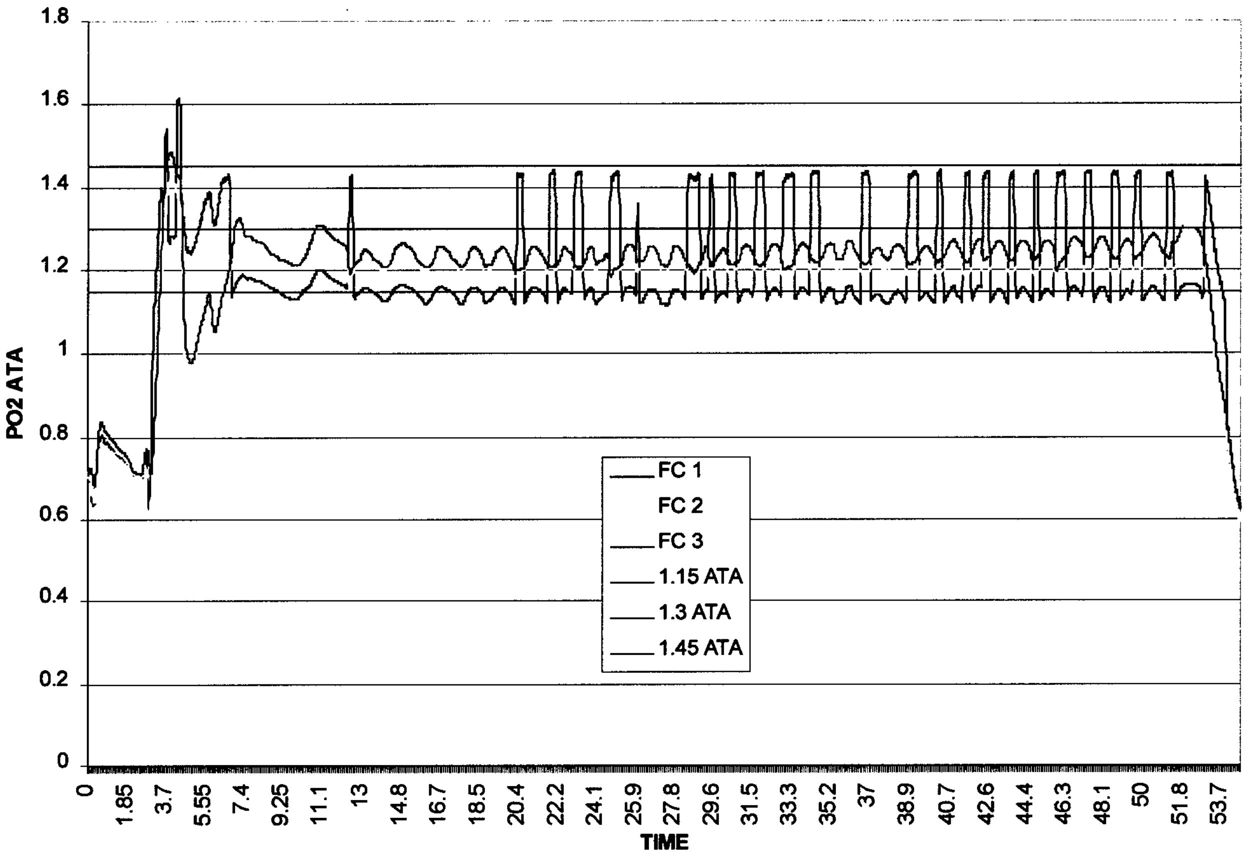

Figure 2. Diver Profile During Descent breathing chamber air during 50 fsw PEA 957 (file ENG609RB)

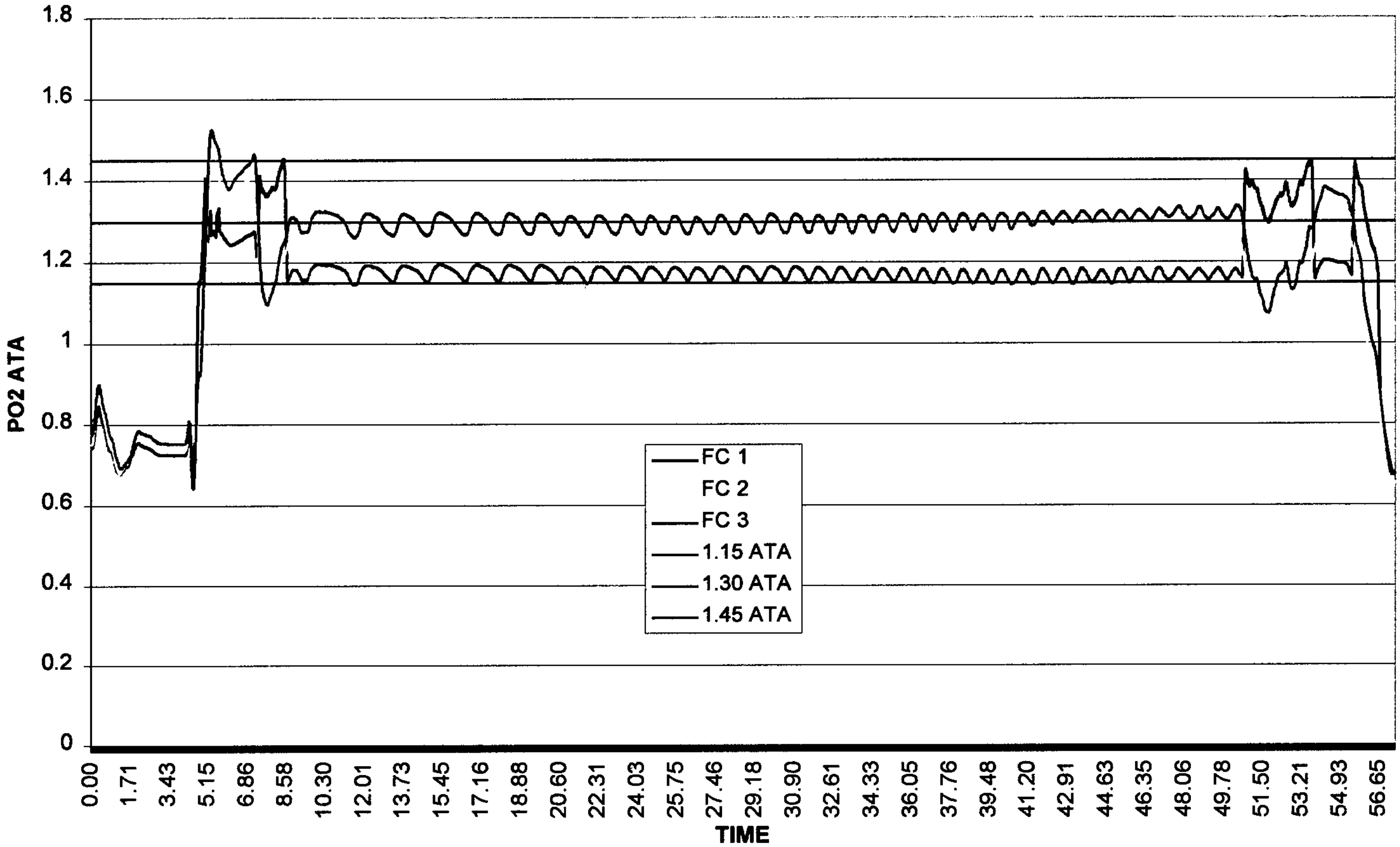

Figure 3. Diver Profile During Descent breathing chamber air during 50 fsw PEA 957 (file ENG610RB)

Table 3 shows minimum and maximum MK 16 fuel cell PO_2 values over the entire dive. This period encompasses the time from when the diver left the surface (LS) until reaching the surface (RS). These values typically represent maximum overshoot during descent and minimum undershoot during ascent.

TABLE 3. Minimum and Maximum PO_2 Values Recorded during 50 fsw N_2O_2 dives.

PEA		FC 1	FC 2	FC 3
419	MIN DIVE	0.61	0.62	0.62
	MAX DIVE	1.48	1.51	1.54
957	MIN DIVE	0.62	0.49	0.48
	MAX DIVE	1.76	1.64	1.68
CTI-1	MIN DIVE	0.70	0.54	0.67
	MAX DIVE	1.68	1.37	1.43
0700	MIN DIVE	0.57	0.59	0.65
	MAX DIVE	1.40	1.49	1.39

Time period covered was from left surface (LS) to reached surface (RS). These values represent maximum overshoot on descent, and minimum undershoot on ascent.
MIN = minimum PO_2 recorded during total dive;
MAX = maximum PO_2 recorded during total dive.

100 fsw

Eighteen dives were conducted at 100 fsw in the OSF: one dive was aborted because the diver suspected a "caustic cocktail" although no discrepancies were discovered post dive. The DAS computers did not record one dive and those data were lost. This left 16 data acquisition dives; their results are presented below. The average BT for this series of dives was approximately 50 minutes. The average Total Dive Time (TDT) for this series of dives was approximately 70 minutes. The difference between TDT and BT is made up by decompression time.

Across nine dives, we achieved a 44.3 fpm average rate of descent, with a range of 32.5 to 55.6 fpm. The average depth of switching from 0.75 to 1.3 ATA PO_2 control set point was 30.8 fsw with a range of 28.2 to 32.4 fsw. The average rate of ascent achieved from 100 fsw to the first decompression stop was 27.5 fpm, with a range of 23.3 to 33.5 fpm. The average depth of switching back from 1.3 to 0.75 PO_2 control set point on ascent was 15.5 feet of seawater, with a range of 13.0 to16.5 fsw.

During the 100 fsw dives, the divers pedaled at workloads ranging from 15 to 100 watts. Average $\dot{V}O_2$ was 1.8 L/min with a range of 0.89 to 3.28 L/min.

The overall average PO_2 overshoot reached during descent was to 1.54 ATA PO_2. The respective average overshoots for PEA 0700 and PEA CTI-1 were to 1.51 ATA and 1.57 ATA. The maximum overshoot for any single MK 16 fuel cell was to 1.72 ATA PO_2. In all instances where the overshoot exceeded 1.40 ATA, the time required for the diver to breathe the UBA down until UBA O_2 sensor read below 1.40 ATA was less than three minutes.

Tables 4 and 5 respectively show the average PO_2 recorded for each of the three UBA fuel cells over the first 10 control cycles and over the entire controlling period at depth. Table 6 shows the maximum and minimum MK 16 fuel cell PO_2 values over the entire dive (LS - RS).

TABLE 4. PO_2 Average during First 10 Control Cycles at 100 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
0700	AVG 10 (SD)	[9] 1.31 (0.02)	[9] 1.21 (0.04)	[9] 1.29 (0.03)
	MIN 10	1.23	1.11	1.21
	MAX 10	1.39	1.32	1.37
CTI-1	AVG 10 (SD)	[8] 1.28 (0.06)	[8] 1.32 (0.04)	[8] 1.30 (0.04)
	MIN 10	1.15	1.21	1.22
	MAX 10	1.42	1.46	1.41

AVG 10 = Average PO_2 over First 10 control cycles;
MIN 10 = minimum PO_2 recorded during 1st 10 control cycles;
MAX 10 = maximum PO_2 recorded during 1st 10 control cycles;
numbers in [ ] indicate the sample size;
numbers in ( ) indicate one standard deviation.

TABLE 5. PO_2 Average over all Control Cycles at 100 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
0700	AVG ALL (SD)	[9] 1.32 (0.03)	[9] 1.18 (0.03)	[9] 1.29 (0.03)
	MIN ALL	1.23	1.07	1.21
	MAX ALL	1.66	1.32	1.39
CTI-1	AVG ALL (SD)	[7] 1.25 (0.06)	[7] 1.32 (0.04)	[7] 1.35 (0.14)
	MIN ALL	1.11	1.21	1.22
	MAX ALL	1.42	1.46	1.41

AVG ALL = Average PO_2 over entire time at 100 fsw after UBA stabilization;
MIN 10 = minimum PO_2 recorded during entire time at 100 fsw after UBA stabilization;
MAX 10 = maximum PO_2 recorded during entire time at 100 fsw after UBA stabilization;
numbers in [ ] indicate the sample size;
numbers in ( ) indicate one standard deviation.

TABLE 6. Minimum and Maximum PO_2 Values Recorded during 100 fsw N_2O_2 dives.

PEA		FC 1	FC 2	FC 3
0700	MIN DIVE	0.69	0.53	0.59
	MAX DIVE	1.64	1.56	1.57
CTI-1	MIN DIVE	0.57	0.60	0.62
	MAX DIVE	1.72	1.67	1.57

The time period covered, diver left the surface (LS) to diver reached surface (RS). These values represent maximum overshoot on descent, and minimum undershoot on ascent.
MIN = minimum PO_2 recorded during total dive;
MAX = maximum PO_2 recorded during total dive.

After UBA stabilization, the time weighted average PO_2 remained within 1.30 +/- 0.05 ATA on all 100 fsw dives with the exception of fuel cell No. 2 in PEA 0700, for which the time weighted average PO_2 was less than the lower control band limit of 1.25 ATA.

After UBA stabilization, the PO_2 range did not fall below 1.15 ATA with the exception of fuel cell No. 2 in PEA 0700 during the 100 fsw dives. During this series of dives, this fuel cell and PEA combination consistently read on the low side, particularly in comparison to the other fuel cells.

After UBA stabilization, the PO_2 range it did not exceed 1.45 ATA with the exception to fuel cell No. 2 PEA CTI-1 during the 100 fsw dives.

During descent, the PO_2 did not exceed 1.76 ATA on any of the 100 fsw dives. During ascent the PO_2 did not go below 0.48 ATA on any of the 100 fsw dives. These values are well within the 1.9 and 0.2 ATA PO_2 maximum and minimum values during descent and ascent respectively.

200 fsw

Ten Heliox dives were conducted at 200 fsw. Of these dives, only one was aborted for diver discomfort in the UBA, although no malfunction was discovered during post dive maintenance. This left nine data acquisition dives; their results are presented below. The average BT for this series of dives was approximately 28 minutes. The average TDT for this series of dives was approximately 2:17 (hrs:min).

Across 10 dives, we achieved a 30.4 fpm average rate of descent, with a range of 15.2 to 41.0 fpm. The average depth of switching from 0.75 to 1.3 ATA PO_2 control set point was 30.5 fsw, with a range of 28.9 to 31.7 fsw. The average ascent rate from 200 feet to the first decompression stop was 28.7 fsw, with a range of 24.9 to 34.5 fpm. The average depth of switching back from 1.3 to 0.75 ATA PO_2 control set point on ascent was 15.6 fsw, with a range of 12.6 to 16.4 fsw.

During the 200 fsw dives the divers pedaled at a constant workload between 30 and 70 watts, based on previous dives. Oxygen consumption average to 1.78 L/min, with a range of 1.20 to 2.39 L/min.

The respective average overshoots for PEA 419 and PEA 957 were 1.57 and 1.56 ATA. The maximum overshoot for any single fuel cell was 1.69 ATA. In all instances where the overshoot exceeded 1.40 ATA, the time required for the diver to breathe the UBA down below 1.40 ATA was less than six minutes. The average time for all fuel cells to register less than 1.40 ATA was slightly less than 2.5 minutes, with a range of 0 to 5.93 minutes.

Table 7 shows average PO_2 values for all three MK 16 fuel cells for that particular PEA during 10 control cycles. The minimum and maximum values displayed are those occurring during the first 10 control cycles, and represent the limits of the UBA control.

TABLE 7. PO_2 Average during First 10 Control Cycles at 200 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
419	AVG 10 (SD)	[4] 1.31 (0.01)	[4] 1.25 (0.04)	[4] 1.28 (0.01)
	MIN 10	1.23	1.13	1.20
	MAX 10	1.38	1.34	1.34
957	AVG 10 (SD)	[5] 1.30 (0.04)	[5] 1.23 (0.01)	[5] 1.26 (0.03)
	MIN 10	1.18	1.15	1.4
	MAX 10	1.41	1.3	1.36

AVG 10 = Average PO_2 over 1st 10 control cycles;
MIN 10 = minimum PO_2 recorded during First 10 control cycles;
MAX 10 = maximum PO_2 recorded during First 10 control cycles;
numbers in [ ] indicate the sample size;
numbers in ( ) indicate one standard deviation.

After UBA stabilization, the time weighted average PO_2 remained within 1.30 ± 0.05 ATA on all 200 fsw dives, with the exception of fuel cell No. 2 in PEA 957. For this fuel cell the time weighted average PO_2 was less than the lower time weighted average of 1.25 ATA PO_2.

Table 8 shows average PO_2 values for all three UBA fuel cells for the entire bottom control time. The minimum and maximum values shown are those recorded during this bottom control time.

TABLE 8. PO_2 Average Overall Control Cycles at 200 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
419	AVG ALL (SD)	[4] 1.31 (0.01)	[4] 1.25 (0.05)	[4] 1.27 (0.01)
	MIN ALL	1.23	1.12	1.17
	MAX ALL	1.40	1.37	1.34
957	AVG ALL (SD)	[5] 1.30 (0.04)	[5] 1.22 (0.02)	[5] 1.25 (0.03)
	MIN ALL	1.18	1.13	1.14
	MAX ALL	1.41	1.33	1.36

AVG ALL = Average PO_2 over entire time at 50 fsw after UBA stabilization;
MIN 10 = minimum PO_2 recorded during first 10 control cycles;
MAX 10 = maximum PO_2 recorded during first 10 control cycles;
numbers in [ ] indicate the sample size;
numbers in ( ) indicate one standard deviation.

Table 9 shows minimum and maximum MK 16 fuel cell values over the entire dive from LS to RS. These values represent maximum overshoot during descent and minimum undershoot during an ascent.

TABLE 9. Minimum and Maximum PO_2 Values Recorded during Entire Dive at 200 fsw (Maximum Depth) HeO_2 dives.

PEA		FC 1	FC 2	FC 3
419	MIN DIVE	0.74	0.68	0.70
	MAX DIVE	1.69	1.56	1.67
957	MIN DIVE	0.66	0.68	0.66
	MAX DIVE	1.69	1.60	1.69

Time period covered was from left surface (LS) to reached surface (RS). These values represent maximum overshoot on descent, and minimum undershoot on ascent.
MIN = minimum PO_2 recorded during total dive;
MAX = maximum PO_2 recorded during total dive.

During descent the PO_2 did not exceed 1.69 ATA on any at 200 fsw dives. The PO_2 overshoot remained below the 1.9 ATA control band goal, although the descent rate was less than the goal of 60 fpm (30.4 fpm), average overshoot was only to 1.56 ATA. During ascent, the PO_2 did not go below 0.64 ATA on any of the 200 fsw dives. Undershoot on ascent was never less than 0.66 ATA, well above the specified known control band parameters for ascent. Average rate of ascent from maximum depth to the first decompression stop was 28.7 fpm, very close to the goal of 30 fpm. These values are well within the 1.9 and 0.2 ATA maximum and minimum values during descent and ascent respectively for the 200 fsw dives.

300 fsw

Eight dives were conducted at 300 fsw. This series of dives was divided into three separate classes based on the work rates (moderately working diver, minimally working diver, and resting diver). Work was based upon previously determined work loads as all these divers had made the entire series of dives (50, 100, and 200 fsw). The average bottom time for the moderately working diver (n=4) was 0:15::59 (hrs:min::sec). Respective bottom times for the minimally working diver (n=2) and the resting diver (n=2) were 0:06::58 and 0:11::53. The average TDT for this series of dives was 3:17::00. Respective total dive time, broken down by work rates, was 4:05::00, 1:53::00, and 3:02::00 for the moderately working, minimally working, and resting diver.

Across all dives, we obtained an average descent rate of 48.4 fpm, with a range of 42.3 to 54.4 fpm. The average depth of switching from 0.75 to 1.3 ATA PO_2 control set point was 30.6 fsw, with a range of 29.7 to 32.4 fsw. The average rate the ascent achieved from 300 feet to the first decompression stop was 28.4 fpm, with a range of 27.0 to 28.9 fpm. The average depth of switching back from 1.3 to 0.75 ATA PO_2 control set point on ascent was 16.7 fsw, with a range of 15.9 to 17.6 fsw.

During the 300 fsw dives, the divers pedaled at workloads ranging from 0 to 70 watts. Oxygen consumption averaged 1.05 L/min, with a range of 0.76 to 1.49 L/min for the moderately working divers (30 to 70 watts). During the two minimally working dives, divers worked at the lowest watt setting (10 watts) on the cycle ergometers to determine the time required to breathe the UBA down from its overshoot to 1.4 ATA PO_2 using a minimal workload. These divers started their ascent once both UBAs had sensor readings below 1.4 ATA PO_2. During both the resting dives and minimally working dives, O_2 consumption could not be calculated during these dives because O_2 bottle pressure did not change measurably.

The average overshoot for PEA 419 was 1.87 ATA and for PEA 957, 1.86 ATA. The time required for the diver to breathe the UBA down below 1.40 ATA ranged from four to 13.4 minutes. The only exception to this was fuel cell No. 2 PEA 419. On two of the eight dives, fuel cell No. 2 registered greater than 1.40 ATA PO_2 throughout the entire bottom time. Because the divers worked at three different work rates, the time required to breathe the UBA down from overshoot on descent to 1.40 ATA PO_2 is further broken down by work rate. Table 10 shows the difference in time to breathe the

UBA down from overshoot to 1.40 ATA for moderately working, minimally working, and resting divers (no work).

Table 10. Time in minutes to breathe UBA down from maximum overshoot on descent to 1.40 ATA during 300 fsw Heliox dives.

WORK RATE	FUEL CELL					
	FC 1		FC 2		FC 3	
	PEA 419	PEA 957	PEA 419	PEA 957	PEA 419	PEA 957
Moderate Work	4.5	5.68	4.77	5.68	4.57	5.29
	4.45	4.28	4.32	4.2	4.6	4.00
Minimal Work	4.92	5.53	---	5.58	4.42	5.33
No Work	12.5	13.3	---	13.4	12.4	13.2

There was insufficient bottom time at 300 fsw for the UBA to perform 10 control cycles. All values reported here are for less than 10 control cycles. After UBA stabilization, the time weighted average PO_2 remained within 1.30 +/- 0.05 ATA on all 300 fsw dives with the exception of fuel cell No. 3 PEA 419. Table 11 shows average PO_2 for all three UBA fuel cells during the entire bottom control time at 300 fsw for all "working" dives. The minimum and maximum PO_2 obtained seen in Table 12 represent the limits of the UBA, over the entire dive (LS - RS). These values usually represent maximum overshoot during descent and minimum undershoot during ascent.

TABLE 11. PO_2 Average Over All Control Cycles at 300 fsw stabilized (Maximum Depth).

PEA		FC 1	FC 2	FC 3
419	AVG CC (SD)	[3] 1.34 (0.06)	[3] 1.34 (0.06)	[3] 1.36 (0.04)
	MIN CC	1.25	1.25	1.27
	MAX CC	1.43	1.47	1.44
957	AVG CC (SD)	*	[3] 1.32 (0.04)	[3] 1.27 (0.02)
	MIN CC		1.23	1.17
	MAX CC		1.48	1.40

AVG CC = Average over all control cycles during time at maximum depth. Because of the short bottom time experienced during the 300 fsw dives, 10 control cycles were not completed.
AVG CC = Average over all control cycles;
MIN CC = minimum PO_2 recorded all control cycles at maximum depth;
MAX CC = maximum PO_2 recorded during all control cycles at maximum depth;
numbers in [ ] indicate the sample size;
numbers in ( ) indicate one standard deviation;
***FC 1 for PEA 957 had voltage spikes in all dives. Therefore, the only fuel cell recorded was for PEA 419.**

TABLE 12. Minimum and Maximum PO_2 Values Recorded during Entire Dive at 300 fsw (Maximum Depth) HeO_2 dives.

PEA		FC 1	FC 2	FC 3
419	MIN DIVE	0.75	*1.21	0.75
	MAX DIVE	1.94	1.95	1.94
957	MIN DIVE	0.69	0.64	0.68
	MAX DIVE	1.95	1.98	1.91

Time period covered was from left surface (LS) to reached surface (RS);
MIN = minimum PO_2 recorded during total dive;
MAX = maximum PO_2 recorded during total dive.
These values represent maximum overshoot on descent, and minimum undershoot on ascent.
***The PO_2 readings recorded from fuel cell No. 2 do not accurately or correctly reflect the PO_2 in the UBA. This is most likely again due to errors within the "Electronic signal splitter box".**

The first four dives conducted at 300 fsw were based on previously determined work rates and are considered to represent the moderately working diver. The next two dives made at 300 fsw represented the resting diver. The last two dives represented the minimally working diver. The results of these three classes of dives are presented in Table 13.

TABLE 13. PO_2 Average during three different work rates at 300 fsw (Maximum Depth).

PEA	Workload		FC 1	FC 2	FC 3
ALL	Working	Avg	[6] 1.36 (0.06)	[6] 1.32 (0.17)	[6] 1.32 (0.05)
		Min	1.25	1.23	1.17
		Max	1.77	1.76	1.44
	Moderate Work	Avg	[4] 1.39 (0.04)	[4] 1.36 (0.05)	[4] 1.33 (0.06)
		Min	1.26	1.23	1.17
		Max	1.77	1.48	1.44
	Minimal Work	Avg	[2] 1.29 (0.02)	[2] 1.50 (0.33)	[2] 1.29 (0.04)
		Min	1.25	1.26	1.24
		Max	1.34	1.76	1.36
	No Work	Avg	#[1] 1.64 (0.07)	[2] 1.73 (<0.00)	[2] 1.63 (0.06)
		Min	1.48	1.63	1.49
		Max	1.88	1.90	1.80

Working=Both the moderately working dives and the minimally working dives averaged for the working workload.
AVG CC = Average over all control cycles;
MIN CC = minimum PO_2 recorded all control cycles at maximum depth;
MAX CC = maximum PO_2 recorded during all control cycles at maximum depth;
numbers in [ ] indicate the sample size;
numbers in ( ) indicate one standard deviation;
 # = PEA 419 fuel cell No. 1 only. Because fuel cell No. 1 had voltage spikes during all dives, only fuel cell No. 1 for PEA 419 is shown.

During descent, PO_2 exceeded 1.9 ATA on three of the eight dives. The single maximum PO_2 on any dive was 1.98 ATA. During ascent the PO_2 did not go below 0.64 ATA on any of the 300 fsw dives. Although ascent PO_2 is how well within the minimum limit, descent PO_2 overshoot exceeded the maximum 1.9 ATA over 33% of the time of during this series of 300 fsw dives.

DISCUSSION

GENERAL

The MK 16 PEA utilizes true voting logic to determine if the UBA is outside control band PO_2 limits. This voting logic works in the following manner. The PEA always evaluates all three fuel cells. If any one of these fuel cells is outside the control band it

simply ignores it. If more than one fuel cell is outside the control band, the PEA then determines the appropriate course of action. If two or more fuel cells read **above the upper control band**, then the appropriate primary display is displayed and no oxygen is added (i.e., the oxygen add valve does not open). If two or more fuel cells read **below the lower control band**, then the appropriate primary display is displayed and the oxygen add valve opens. Hence, this report looks at the capability of the PEA to maintain the oxygen level within the control band.

SET POINT SWITCHOVER

On all dives and all gas mixes, the PEA reliably switched from control set points of 0.75 ATA PO_2 to 1.3 ATA PO_2 on descent, and back to 0.75 ATA PO_2 control set point on ascent within the performance goal of ± 2 fsw (± 0.6 msw).

O_2 CONTROL

PO_2 Range

The time weighted average PO_2 for the MK 16 MOD 0 after UBA stabilization was maintained at 1.30 ± 0.05 ATA for all depths and gas mixtures in at least two of the three fuel cells at all times. Again, because of the unique nature of the MK 16 voting logic, only two of the three fuel cells need be within the 1.30 ± 0.05 ATA control band for the UBA to achieve the stated performance goal.

The MK 16 MOD 0 maintained the PO_2 within the control band of 1.15 – 1.45 ATA (high set point) at all depths and gas mixtures in at least two of the three fuel cells at all times. Again, because of the voting logic, if two of the three fuel cells reads within the control band, then the performance goal is achieved.

Descent

Upon descent, the PO_2 did not exceed 1.9 ATA at 50 or 100 fsw in Nitrox or at 200 fsw in heliox. However, at 300 fsw in heliox the PO_2 reached to 1.98 ATA and remained there for anywhere from 4 minutes to as long as 13 minutes depending on diver's work level. The descent rate goal of 60 fpm was not obtained during this study. Therefore, a wide range of descent rates was obtained (6.9 – 55.6 fpm) because of the OSF volume and the result of various diver difficulties in equalizing during descent. This however provided some insight into PO_2 overshoot on descent. Although not supported with definitive results, it would appear intuitively that the slower descent rates allow for a higher overshoot. With a slower descent, the PO_2 rises due to pressure changes, allowing for the O_2 add valve to remain open longer after the UBA reached the control set point switch-over depth. This would argue for divers to try to achieve descent rates close to the 60 fpm goal.

Ascent

Upon ascent, the PO_2 did not fall below 0.2 ATA thereby meeting this performance goal. Although the ascent rate goal of 30 fpm was not obtained (average over all dives, all depths was 27.1 fpm), it is close enough to the goal that the shortfall should be considered insignificant. Additionally, the single lowest ascent undershoot PO_2 achieved was 0.48 ATA, well above the minimum performance goal.

Fuel Cell Variance

On several occasions, one fuel cell out of three was outside the control parameters. However, this does not affect the UBA O_2 control because of the voting logic used with the PEA. Discrepancies in fuel cell readings may be due to variance in the performance of fuel cells. Extensive research has been previously done at NEDU to compare the fuel cells now currently authorized for use in the MK 16 UBA[12]. From this report it was demonstrated that both fuel cells currently used in the MK 16 exhibit a degradation in output voltage as a function of depth and oxygen partial pressure. This degradation ranged from 4.6 to 7.3%, depending on depth and PO_2. In terms of ATA for degradation as a function of PO_2, this equated to a range of 0.05 - 0.06 ATA for a 0.75 ATA PO_2 atmosphere (slightly higher than the high set point). This output voltage degradation could account for much of the discrepancies that were recorded outside control band limits for the 1.3 ATA PO_2 PEA.

Another important factor in the fuel cell readings and O_2 control is the UBA calibration procedures. A critical component of UBA sensor calibration is the amount of time each sensor is exposed to the calibration gas prior to adjusting and setting the UBA electronics assembly. If too short a period is allowed, the sensor will read at less than the desired PO_2 and subsequent readings will be off. Appropriate procedures, which have been developed and evaluated; and should be used for set-up of the MK 16 MOD 0[10].

CONCLUSIONS / RECOMMENDATIONS

1. The MK 16 MOD 0 PEA controls the PO_2 according to the PO_2 control band goals.

2. Calibration procedures must be carefully followed, particularly the time O_2 sensors are exposed to the calibration gas.

3. Recommend that the MK 16 MOD 0 1.3 ATA Primary Electronics Assembly be adopted for Fleet usage.

4. Recommend continue the current operational tactic of “bumping” O_2 up until the primary display shows a flashing green light prior to starting ascent from the bottom if tactical situation permits.

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